Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 70 (2015) 245 – 248

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

High-order acoustic Bessel beam generation by spiral gratings

N. Jiménez[a,*], V. J. Sánchez-Morcillo[a], R. Picó[a], L. M. Garcia-Raffi[b], V. Romero-Garcia[c], K. Staliunas[d]

[a]*IGIC, Universitat Politècnica de València c/ Paranimf 1, Grao de Gandia, 46730, Spain*
[b]*IUMPA, Universitat Politècnica de València - Camí de Vera s/n, Valencia, 46022, Spain*
[c]*LUNAM Universit, CNRS, LAUM UMR 6613, Av. O. Messiaen, Le Mans, 72085 , France*
[d]*ICREA, Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, Colom, 11, Terrassa, 08222, Spain*

Abstract

We report first-order Bessel beam formation by means of a novel passive acoustic device. The scattering of plane waves by a spiral grating leads to the creation of an acoustic vortex with a pressure null on-axis. Numerical simulations and experimental results report the formation of an acoustic vortex in the near field as the phase presents a screw dislocation and the field is null at the axis. The control of the vorticity and the characteristics of Bessel beams are useful for potential applications on low-cost acoustic tweezers and acoustic radiation force applications.
© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Scientific Committee of ICU 2015
Keywords: Spiral grating; Bessel beam; Acoustic vortex
PACS: 43.20.Fn, 43.35.Bf

1. Introduction

Bessel beams, are usually proposed for many applications due to their diffraction propagation properties Jimenez et al. (2014). In the ideal case, the field propagates invariantly, i.e. without any diffracting broadening in free space propagation. High-Order Bessel Beams (*HOBB*) present a linear variation on the azimuthal phase and a minimum of pressure amplitude in the radial axis caused by a phase singularity. Due to this, an acoustic vortex is generated along propagation with a spatial phase dependence that cannot be generated by axisymmetric radiating sources. Phase dislocations were first proposed in Nye et al. (1974). Several configurations have been proposed since then Hefner et al. (1999); Gspan et al. (2004). The interaction of *HOBB* with particles have been widely studied in the exhaustive collection of works of F. G. Mitri and G. T. Silva among others. Two main remarkable effects have been reported: (1) the transference of orbital momentum from the acoustical vortex to the particle Mitri et al. (2012), and (2) the appearance of negative axial acoustic radiation forces Mitri (2009). In this work we propose a passive system for the formation of a first-order Bessel beam: a grating with the shape of a spiral. The diffracted pressure field by the

* Corresponding author. Tel.: +34 962-849-300 ; fax: +34 962-649-309.
E-mail address: nojigon@epsg.upv.es

1875-3892 © 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.146

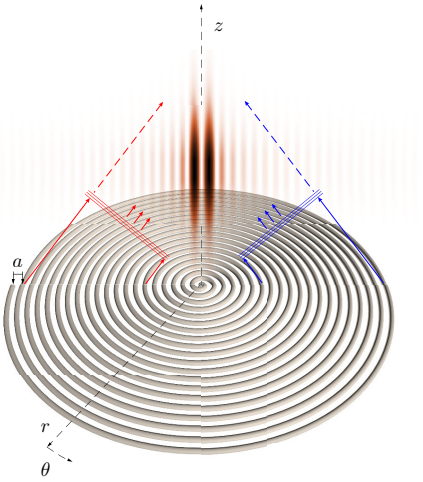


Fig. 1: Scheme of the first-order Bessel beam formation by the Archimedes' spiral grating. The incident plane wave is scattered into a converging conical wavefront. A corkscrew dislocation is produced, leading to an acoustic vortex and a pressure node at the axis in $r = 0$.

grating generates an acoustic vortex with a characteristic screw dislocation. The device is tested numerically and an experimental setup is proposed in the ultrasound regime to measure the acoustic field.

2. Spiral Grating

A grating with a spiral shape is proposed for Bessel beam generation. The grating is aligned and placed next to a flat ultrasonic transducer in such a way that the incoming wave is transformed into a helical wave. The shape of the profile perforated in the grating is an Archimedean spiral as shown in Fig.1. Archimedean spirals are a family of spirals described in general by a polar equation:

$$r(\theta) = \frac{ma}{2\pi}\theta \tag{1}$$

where a is the grating wavelength and corresponds to the radial distance to the center between two successive turns of the spiral $r(\theta_0) - r(\theta_0 - 2\pi) = a$, m is the order of turn ($m \geq 1$).

The acoustic field generated by the grating in the far field is an acoustic vortex and, in general, it can be represented by a Bessel beams of the first order:

$$p(r, \theta, z) = A_0 J_1(k_r r) \exp(ik_z z \pm i\theta) \tag{2}$$

where A_0 is the amplitude and z is the axial component. The spiral is centered at the axis in $r = 0$. The linear variation in the azimuthal component of the phase is the responsible of the phase dislocation in the axis and the "±" sign is related to the chirality (handedness) of the spiral. The axial (k_z) and transverse (k_r) components of the wavevector $k = \sqrt{k_z^2 + k_r^2}$ are expressed as:

$$k_z = \frac{2\pi}{a\lambda}\sqrt{1 - \left(\frac{\lambda}{a}\right)^2}\ ,\ k_r = \frac{2\pi}{a}. \tag{3}$$

where λ is the wavelength. In the case of a real structure with finite aperture, the pressure field is a Bessel-like beam and it is bounded in the axial direction. The amplitude A_0 depends on the specific characteristics of the grating. The vortex intensity pattern is characterized by a central dark spot surrounded by intensity rings. The pressure field is null at the axis as shown in Fig.1. By contrast, the zeroth-order Bessel beam has a pressure maximum at the axis. This is due to the destructive interference of a phase-rotating conical wavefront.

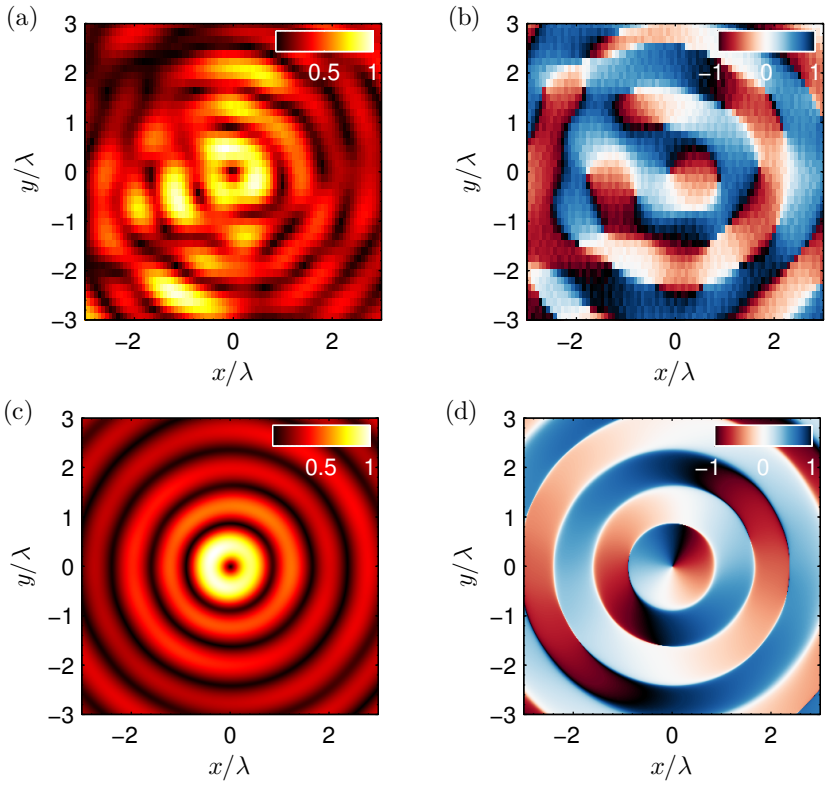


Fig. 2: Transversal distribution of the acoustic field at distance $z = 10/\lambda$. (a)-(b) Numerical and (c)-(d) experimental results of the magnitude and phase, respectively. Colorbars in normalized units (p/p_0 and ϕ/π).

3. Experimental results

Laser cutting techniques have been used to design the spiral profile over a stainless thin steel plate of $0.8mm$. The thickness of the scatterers is $\Delta r = 0.75mm$ and the grating wavelength $a = 1mm$. These values lead to a width of $a - \Delta r = 0.25mm$ of the open part. The spiral turns 20 times ($1 \leq m \leq 20$) and the grating radius is $25mm$. The spiral plate is aligned and placed in front of a flat piston ultrasound flat transducer. The separation distance between the grating and the source plane was adjusted to $0.5mm$. The wave transmitted through the grating is an acoustic vortex.

Figure 2 summarizes the experimental and numerical results. All the subfigures correspond to representations of the acoustic field in a transverse plane to the axis. In Fig. 2(c) the numerical result for the amplitude of the field conformed by the spiral grating is observed. The pattern matches with the characteristic first order Bessel beam with null amplitude in its axis and a set of circular shape on pressure maxima with increasing radius. In Fig. 2 (a) the equivalent experimental results are presented. Both results show good agreement except for some minor discrepancies are observed in the experimental measurements and can be produced by the misalignment between the grating and the transducer plane. The phase of the field is presented in Fig. 2(c) for experimental results and n Fig. 2(d) for the numerical ones. The characteristic screw phase dislocation at the center is observed: a complete turn around a circle centered on the axis represents a linear and continuous variation from 0 to 2π of the phase. Remark that a shift of π in phase is observed between any point and its symmetric respect to the central axis.

A detailed transversal field profile is presented in Fig. 3. The transversal cut (circles) was selected for an azimuthal angle in the (y, x) plane at $\theta = -3^o$, and a fit with the analytical solution (continuous line) is presented. The traversal profile correctly agrees the first order Bessel beam of equation (3). Although minor differences are found for the lobe

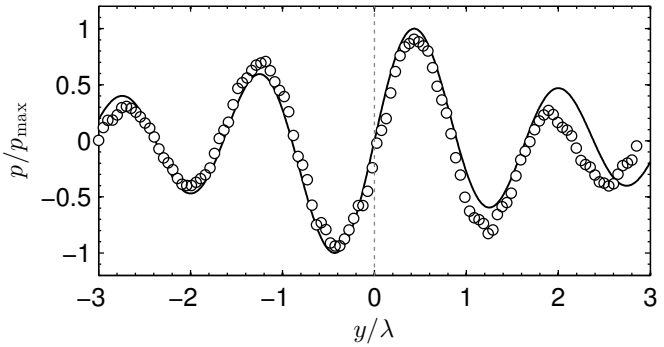


Fig. 3: Transversal cut of the pressure field normalized to the maximum for (continuous line) the analytic expression of the first-order Bessel beam and (circles) the experimental results. The vertical dotted line represents the center of the axis were the field is null.

amplitude on the positive axis y, the main features of the high order Bessel beam, i.e. its central zero and rotational vortex, are correctly reproduced by the proposed experimental setup.

4. Conclusions

The formation of first-order Bessel beams is reported by scattering of plane waves on an Archimedes' spiral grating. Good agreement between experimental measurements and numerical simulations is found for the acoustic pressure field. Truncated first order Bessel beams, are characterized experimentally. The characteristic null in the field all over it axis and the screw dislocation are demonstrated by measurements of the acoustic field.

Acknowledgements

The work was supported by ESA Contract 4000110685/14/NL/SC. LMGR Acknowledges Supported by MINECO and FEDER, under Grant MTM2012-36740-c02-02.

References

Jiménez N, Romero-García V, Picó R, Cebrecos A, Sánchez-Morcillo VJ, Garcia-Raffi LM, Sánchez-Pérez JV and Staliunas K. Acoustic Bessel-like beam formation by an axisymmetric grating. *EPL* 2014; 106, 24005.

Nye JF and Berry MV, Dislocations in wave trains. *Proc. R. Soc. A* 1974; 336,165-90.

Hefner BT and Marston PL. An acoustical helicoidal wave transducer with applications for the alignment of ultrasonic and underwater systems. *J. Acoust. Soc. Am.* 1999; 106, 6.

Gspan S, Meyer A, Bernet S and Ritsch-Marte M. Optoacoustic generation of a helicoidal ultrasonic beam. *J. Acoust. Soc. Am.* 2004; 115, 3.

Mitri, FG, Lobo TP and Silva GT. Axial acoustic radiation torque of a Bessel vortex beam on spherical shells. *Phys. Rev. E* 2012; 85, 026602.

Mitri, FG. Acoustic radiation force of high-order Bessel beam standing wave tweezers on a rigid sphere. *Ultrasonics* 2009; 54(1), 419, 20.